Effects of geotextile envelope and perforations on the performance of corrugated drain pipes

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Abstract: Subsurface drainage is an important agriculture drainage measure. It is primary to select suitable drain pipes and envelopes for efficient subsurface drainage. And now, corrugated drains and geotextile envelopes are widely used. However, the effects of geotextile envelopes and perforations on the drainage of corrugated drains are not well understood. This study conducted a series of sand tank experiments of steady-state flow with or without geotextile envelopes and with different perforation patterns. The drainage flow and the profile head distributions were analyzed and compared. Furthermore, the applicability of theoretical formulas, which are used to calculate effective radius considering the resistance of different perforation patterns, was evaluated. Results showed that the geotextile envelope weakened the effect of perforations on streamlines, thereby causing the value of effective radiuses to be close to that of the actual radius. The drainage flow of the drain with a geotextile envelope was six times that of the bare drain. The relationship between drainage flow and opening area could be described by inverse proportional function. Meanwhile, the drainage flow was affected by the perforation arrangement. Drain with small longitudinal perforation spacing had a drainage flow of approximately 15% larger than that with wider longitudinal perforation spacing. The bottom perforations drained out first and most, and the drainage flow of the drain opened at the bottom could be 11% higher than that at the top. Low-efficiency perforations cause higher head loss near the pipe wall. Existing formulas of entrance resistance were not suitable for geotextile-wrapped corrugated drains, the effect of geotextile envelope and orifice entrance loss at perforations should be considered.

Keywords: geotextile envelope, perforation, corrugated drain, effective radius, drain opening, entrance resistance, drainage material
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1 Introduction

Drainage materials (i.e., pipes and envelopes) are important factors that affect the efficiency and lasting performance of subsurface drainage systems[1-3]. The renewal of materials and related theories have promoted the development of drainage technology[4,5]. Now, corrugated plastic pipe wrapped in a geotextile envelope has largely replaced clay tile, concrete tile, smooth plastic pipe, etc. as the first choice, which increases the speed of construction and saves costs[4,6,7].

As actual drains have a finite area of opening on the wall, near the drain there is entrance resistance that has to be considered for an accurate calculation of drainage flow[8]. The amount of entrance resistance was determined by properties of drainage materials, such as opening area, perforation pattern, pipe diameter, envelope thickness, envelope permeability, etc.[6,9] It is essential to clarify the effect of materials on subsurface drainage performance.

For tile and smooth drains, many experiments were conducted and the theoretical researches are relatively sufficient[9]. Smaller gap spacing and larger width will increase drainage flow for tile drains[10,11]. And the effect of opening area, size, arrangement, and envelopes on drainage flow and entrance resistance is clear now for smooth plastic drains[12-15]. Theoretical results considering different perforation arrangements were got with and without envelopes[16,17]. Several experimental studies on corrugated drains have been conducted. Bravo[18] used an electrical analog model to investigate the relative effectiveness of opening area and width, as influenced by the presence of soil within the corrugations and within the openings themselves. Mohammad and Skaggs[19] conducted some sand tank tests to determine the effects of total opening area, perforation location, and gravel envelope on head loss and drainage flow. Bentley and Skaggs[20], Lennoz-Gratin[21], and Sekendar[22] evaluated the entrance resistance of corrugated drains with synthetic envelopes of different thicknesses using sand tanks. Relevant theoretical investigations are few. Dierickx[9] considered the additional resistance of corrugated drains for which the corrugations filled with soil and added it to the expression of smooth drains with circumferential openings. Afrin et al.[23] and Gaj and Madramootoo[24,25] established three-dimensional numerical models to simulate the effect of perforation shape, size, and configuration on drainage flow. However, the effect of perforations on the performance of corrugated drains wrapped with geotextile envelope has not been studied.

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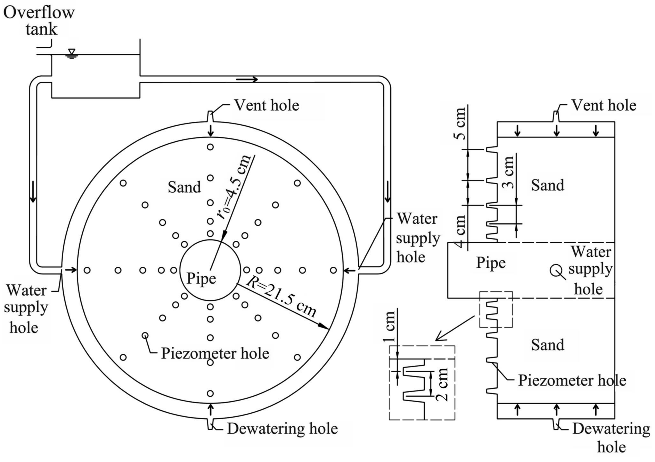
Existing formulas of entrance resistance are all based on the situation that the soil or granular filter is directly in contact with the perforations, and water is drained out through the perforations directly after permeating, which follows Darcy's law[16,26]. Thus, they are more suitable for tile drains and smooth plastic drains that have simple structures. However, it is much more complicated for corrugated drains with the existence of corrugations, especially the continuous porous medium is broken near the drain when the drain is wrapped in geotextile envelopes[27]. Then, the formulas based on Darcy's law may be not appropriate enough. The effect mechanism of geotextile envelope and perforations with corrugated pipes on drainage performance needs further investigation.

So a series of laboratory experiments were carried out, compared the drainage flow and profile water head distribution of corrugated drains with or without geotextile envelope and with different perforations, analyzed their entrance resistance, evaluated the applicability of existing theoretical formulas, and revealed the drainage law and effect mechanism.

2 Materials and methods

2.1 Experimental setup

The experiments were carried out using a cylindrical acrylic sand tank that was made of two concentric cylinders (Figure 1). One side of the cylinders (reverse side) is covered by a flange, and the other side (front with pipe outlet) is covered by a circle plate, wherein a 9 cm diameter pipe mounting hole can be found. The outer cylinder has a vent and a dewatering hole on the top and bottom, respectively. It also has two water supply holes that are connected to the overflow tank by a hose on the left and right sides. The inside dimensions of the inner cylinder, which is used to fill sand, are 43.0 cm in diameter and 21.5 cm in length. On the wall of the inner cylinder, uniformly dense holes exist for water to enter in, and it is covered by a wire mesh inside to prevent sand from flowing out. A gap is left between the inner and outer cylinders to provide an even water head on the edge of the sand.



a. Front view b. Side view

Figure 1 Schematic representation of the sand tank model

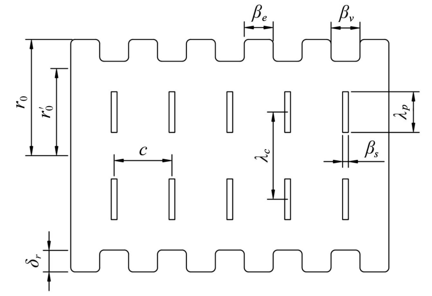
Five circles of piezometers are arranged around the drain hole in the front, and the distance between the piezometers and the drain wall is 1 cm, 3 cm, 6 cm, 10 cm, and 15 cm. The arrangement is symmetrical. Hence, only one side of the piezometers was used in the test.

Besides the piezometers in front, the vent on the top was used to measure the water head applied on the periphery of the sand. At the same time, four piezometers that were drawn out inside the drain were used to measure the water head on the top, middle, and bottom parts of the groove and the top of the ridge outside the drain wall.

Corrugated PE drainage drains with an outer diameter of 90 mm were used in this study. The drains were placed horizontally in the center of the tank. The drain's detailed dimensions and structure diagram are listed in Table 1 and Figure 2, respectively. The envelope used in this study is a spun-bonded filament non-woven fabric with a mass per unit area of 71.25 g/m^2, hydraulic conductivity of 24.19 m/d, and thickness of 0.14 mm. Fine sand was filled in the setup, and its mean saturated hydraulic conductivity is 30.98 m/d with a standard deviation of 2.79 m/d. Its particle-size distribution is shown in Figure 3. A total of 10 treatments with different perforation patterns were tested in this study, as presented in Table 2 and Figure 4. Drains with envelopes were wholly wrapped in two layers of geotextile. For drains without envelopes, it is hard to prevent the sand of poor structures from moving out if do not use any geotextile. So only a

Table 1 Drain structure parameters used in the experiment

Parameter	Larger outer radius/mm	Smaller outer radius/mm	Crest width/mm	Valley width/mm	Valley deep/mm	Wall thickness /mm
Value	45	40	5.35	4.0	4.0	1.0



Note: r_0 is the large outer radius; r'_0 is the smaller outer radius; β_v is the valley width; β_e is the crest width; δ_r is the corrugation depth; c is the perforation spacing in the row; λ_c is the perforation space on the drain circumference; λ_p is the perforation length; β_s is the perforation width. All units in mm.

Figure 2 Definition sketch of the pipe structure and perforations parameters

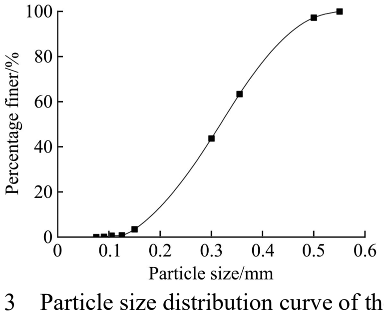


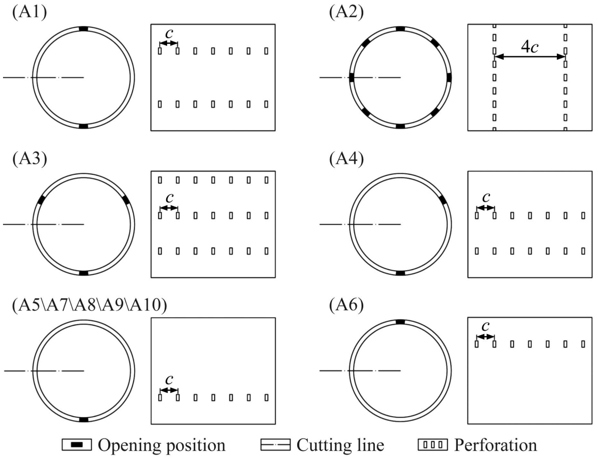
Figure 3 Particle size distribution curve of the sand

Table 2 Summary of treatments in this study

Treatment	Perforation size/mm×mm	Number of longitudinal rows of perforation	Opening area/cm^2·m^{-1}	Perforation rate/%
A1	17.53×2.73	2	88.9	3.14
A2	17.53×2.73	8	88.9	3.14
A3	8.62×2.05	3	56.7	2.01
A4	8.62×2.05	2	37.8	1.34
A5	8.62×2.05	1	18.9	0.67
A6	8.62×2.05	1	18.9	0.67
A7*	8.62×2.05	1	18.9	0.67
A8	1.53×2.05	1	3.4	0.12
A9	3.06×2.05	1	6.7	0.24
A10	4.60×2.05	1	10.0	0.35

Note: * Treatment with no geotextile envelope wrapped.

piece of geotextile as large as the perforation was used by sticking it above the perforation rather than the corrugation. Because the geotextile is thin and the hydraulic conductivity is not much different from that of the sand, this treatment will not make much difference from drains without any geotextile.



Note: In one treatment schematic diagram, the figure on the left is the cross-section and the figure on the right is the spread pipe cutting along the dotted line. The parameters of A1-A10 are listed in Table 2.

Figure 4 Schematic diagram of perforations position of 10 treatments in this study

2.2 Experimental procedure

At first, the sand was compacted from the open flange at a density of 1.67 g/cm^3. Second, the sand tank was erected to make the drain level. Third, the sand was saturated by slowly raising the water level. Then, flow under a low water head was allowed to continue for 24 h to ensure that all the air in the sand is expelled. Subsequently, the overflow tank was adjusted to the desired height, and then drainage flow was monitored until the water flow is stable, which takes approximately 48 h. Then, the drainage flow and water head were measured while recording the water temperature. After that, the supply water head was adjusted for another observation. However, this time, it only took about half an hour to be stable again. After all flow measurements were completed, the supply water head was adjusted to the first value, and the drainage flow was measured again to compare it with the flow measured initially to ensure that the flow has been stable at the beginning.

Each test was conducted under five different overflow elevations that vary from 42 cm to 122 cm above the drain center at an interval of 20 cm. At the end of the tests, the drainage flow was temperature-corrected to 20°C, and the piezometer readings were converted into the head with the center of the drain as a reference.

2.3 Theoretical background

A fictitious drain called an ideal drain with a completely pervious wall is often assumpted in the theoretical and numerical analysis of drainage[8,28]. For an ideal drain, the equipotential lines are concentric circles centered on the drain when running full, if the soil is homogeneous and isotropic, and the flow is radial. Under the above conditions, an equipotential circle that is larger than the drain is taken, the water head between the circle and drain is integrated according to Darcy's law, and then the head difference or radial head loss within the soil can be expressed as,

$$\Delta H=\frac{q}{2\pi K_s}\ln\frac{R}{r} \tag{1}$$

where, ΔH represents the radial hydraulic head loss, cm; q is the drainage flow per unit drain length, cm^2/s; K_s is the saturated hydraulic conductivity of soil, cm/s; R is the radius of the circular equipotential considered, cm; r is the radius of the ideal drain, cm. Meanwhile, the head loss can be given by

$$\Delta H=\frac{q}{K_s}\alpha \tag{2}$$

where, α is the resistance for soil with hydraulic conductivity equal to unity.

However, the real drain is not completely previous, so an additional flow resistance called entrance resistance exists. By introducing the concept of effective radius, which is a smaller radius of an imaginary ideal drain, the head loss caused by entrance resistance can be transformed into the radial resistance of an imaginary soil circle layer between the effective radius and real radius[10]. Then the relationship between entrance resistance and effective radius can be established.

In the fictitious soil circle, R in Equation (1) is replaced with the radius of the real drain r_0, r in Equation (1) is replaced with the effective radius r_e, α in Equation (2) is replaced with entrance resistance α_e, then substitution of ΔH from Equation (1) into Equation (2) gives as,

$$r_e=r_0e^{-2\pi\alpha_e} \tag{3}$$

The entrance resistance of the smooth drain with circumferential openings for a plane boundary is expressed as[26],

$$\alpha_e=\frac{c}{2\pi^2r_0}\ln\frac{2c}{\pi\beta_s}-\frac{1}{2\pi}\left(\frac{c}{2\pi r_0}\right)^2+\frac{c}{2\pi r_0}g\left(\frac{2r_0}{c},\frac{2R}{c}\right) \tag{4}$$

where, α_e is the entrance resistance, dimensionless; c represents the longitudinal perforation spacing, cm; β_s is the perforation width, cm.

$$g\left(\frac{2r_0}{c},\frac{2R}{c}\right)=\frac{1}{\pi}\left[T_1'\left(\frac{2r_0}{c}\right)-1+\sum_{n=2}^{\infty}\frac{1}{n}\left\{T_n'\left(\frac{2r_0}{c}\right)-1+\frac{c}{4\pi r_0(n-1)}\right\}\right] \tag{5}$$

$$T_n'\left(\frac{2r_0}{c}\right)=\frac{K_0(2n\pi r_0/c)I_0(2n\pi R/c)-K_0(2n\pi R/c)I_0(2n\pi r_0/c)}{K_1(2n\pi r_0/c)I_0(2n\pi R/c)-K_0(2n\pi R/c)I_1(2n\pi r_0/c)} \tag{6}$$

where, K_0 and K_1 and I_0 and I_1 are the modified Bessel functions of the second and first kind and zero and first order, respectively; n is a natural number greater than or equal to 2.

Based on Equation (4), Dierickx[9] gave an approximate solution of entrance resistance for a corrugated drain with discontinuous circumferential slits in the valleys as follows:

$$\alpha_e=\frac{c}{2\pi^2r_0}\ln\frac{2c}{\pi\beta_v}-\frac{1}{2\pi}\left(\frac{c}{2\pi r_0}\right)^2+\frac{c}{2\pi N\lambda_p}\ln\frac{2\sinh\frac{2\pi\delta_r}{\beta_v}}{\sin\frac{2\pi\beta_s}{2\beta_v}}-\frac{1}{2\pi}\ln\frac{r_o}{r_o'} \tag{7}$$

where, β_v is the valley width, cm; N is the number of perforation rows; λ_p is the perforation length, cm; δ_r is the corrugation depth, cm; r'_0 is the smaller outer radius, cm.

3 Results and discussion

3.1 Relationship between water head and drainage flow

The relationship between the water head at the periphery of the sand and drainage flow is displayed in Figure 5, which shows a strong linear correlation ($R^2>0.98$) and conforms to the rule reflected by Equation (1). However, with the increase in water head, the increment in drainage flow tends to slow down, especially for the treatments with low opening areas, such as A5, A8, A9, and A10. Moreover, the intercept variations of linear fitting lines are large, however, when the head is at the lowest perforations, drainage flow should be 0. By comparison, the quadratic polynomial is more appropriate to fit ($R^2>0.99$). The fitting formulas are listed in Table 3. Within the range of measuring points, the fitting lines are precise enough, so the drainage flow of different tests under any water heads can be calculated for later comparison.

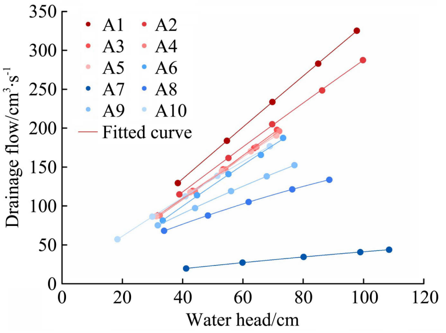


Figure 5 Drainage flow versus water head for all treatments

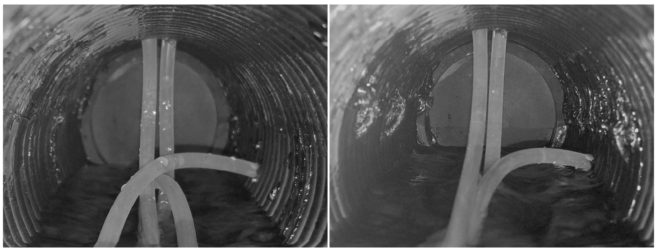
Table 3 Fitting formulas of different treatments

Treatment	Fitting formula	Treatment	Fitting formula
A1	$y=-0.00077x^2+3.40x+0.37$	A6	$y=-0.00311x^2+1.84x-2.87$
A2	$y=-0.00169x^2+3.06x-1.67$	A7	$y=-0.00073x^2+0.46x+1.79$
A3	$y=0.00066x^2+2.67x+3.67$	A8	$y=-0.00444x^2+1.75x+13.86$
A4	$y=0.00106x^2+2.63x+1.36$	A9	$y=-0.00439x^2+2.19x+10.00$
A5	$y=-0.00442x^2+3.06x-4.42$	A10	$y=-0.00390x^2+2.71x+8.38$

Note: *y* is the drainage flow; *x* is the water head.

3.2 Flow condition inside the drain

During experiments, the flow condition inside the drain with different supply water heads was observed. A4, which has perforations at the bottom and upper parts, was taken as an example. As shown in Figure 6a, when the supply water head was low, water first flowed out from the perforations at the bottom, whereas no flow was observed from the perforations at a higher position. As the drainage flow increased with the supply water head, water rushed out from the bottom perforations. At this point, the top perforations began to drain with a much smaller flow (Figure 6b).



a. Photo of A4 with a low supply water head

b. Photo of A4 with a high supply water head

Figure 6 Water current inside the drain

Meanwhile, the water head just outside the pipe wall was monitored using the piezometers connected to the wall (Figure 6). When the drainage flow was low, only the bottom piezometer could be read, the piezometers located on the middle and upper parts could not be read. The upper piezometers only worked when the drainage flow was large enough. It indicated that the valleys of the pipe were not full of water when the drainage flow is low. The water seeping from sand collected beneath the valleys and the air was left at the top. As the drainage flow increased, water gradually filled the valleys because the bottom perforations could not discard too much water, and the air inside was gradually squeezed out.

During the experiments of smooth drains wrapped with thick fiberglass, Watts and Luthin[12] also found that water moved out through the bottom perforations, and they concluded that the fiberglass was permeable enough, which let water move through the envelope past the top row of the perforations and move down. The study of Tiligadas[29] on corrugated drains without envelopes indicated that when the drain flowed partially full, its upper surface was a seepage surface, and consequently surface tension was observed at the soil-air interface, in which case the water could not penetrate through the upper perforations if the available hydraulic head at the upper perforations was not great enough, and a part of streamlines was deflected around the drain and concentrated to the "wet" side of the drain.

In this study, corrugated drains were used and wrapped with geotextile, which made them different. When the corrugated drains were wrapped with geotextile, an annular space was formed between each valley and envelope. Before draining, the annular space was filled with air protected by the geotextile. After the water permeated out the sand, it flowed into the annular space where it could freely flow down under the force of gravity. Therefore, the water will penetrate through the bottom perforations at first. Perforations have a strong ability to drain free water, so when the drainage flow was low, the bottom perforations could drain all the water without the help of upper perforations. As the drainage flow increases, if the bottom perforations could not drain the water immediately, the top perforations will drain as soon as the water level rises to them. Most of the water will drain out from the bottom because the bottom perforations had lower position potential.

3.3 Effect of geotextile envelope on drainage

Figure 7 shows the H-Q curves of A5 and A7, which have the same perforations. A5 is wrapped with a geotextile envelope over its corrugation. For A7, only the perforations are covered with a piece of geotextile to prevent sand from moving. As illustrated in Figure 7, the geotextile envelope can improve the drainage flow of corrugated pipe significantly, although it is less than 0.2 mm thick. Under the same water head, the drainage flow of A5 was about six times that of A7.

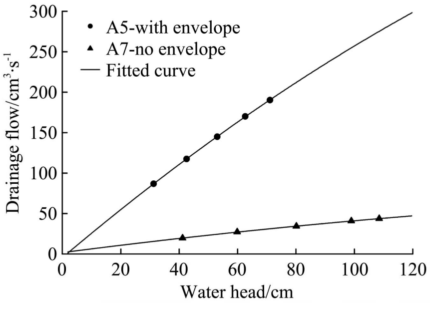
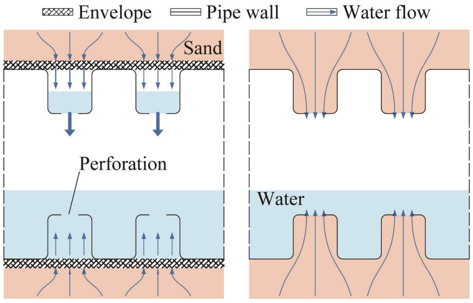


Figure 7 Drainage flow versus water head in treatments with and without an envelope

As shown in Figure 8, the soil condition around the drain pipes with and without envelopes is easy to imagine. According to Section 3.2, an annular space, which was filled with air when it was not draining, was in the valley of A5, and the water flow pattern in the space was free flow. However, for A7, the valley without the protection of geotextile was full of sand where water was vadose. The expansion of the vadose region could cause an additional head loss of A7. Meanwhile, the main reason for the difference in drainage flow may be the seepage surface area. For A7, only the opening area was in direct contact with air, so its seepage surface area was small. For A5, the seepage surface area was dozens of times as much as that of A7, as the interface between geotextile and the valleys of A5 was in direct contact with air. McKyes and Broughton[30] also mentioned that the envelope provided a much larger area for water to enter the valleys. The concentration of streamlines in soil with a small seepage surface was stronger, which caused an additional head loss. For A5, it became free flow in the valley after water penetrates through the geotextile envelope, in which condition it was orifice flow rather than seepage at the perforations, which did not cause too much head loss. Thus, the drainage flow of A5 was much bigger.



a. A5 b. A7

Figure 8 Schematic diagrams of soil condition and streamlines around pipes of A5 and A7

3.4 Effect of perforations on drainage

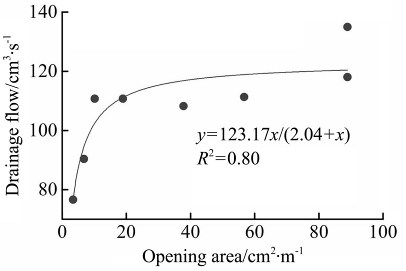
3.4.1 Relationship between opening area and drainage flow

Based on the fitting formulas in Section 3.1, the drainage flow of various experiments with different supply heads can be calculated, so scatter diagrams of the opening area and drainage flow can be drawn (Figure 9). Drainage flow and opening areas have a certain positive correlation. The inverse proportional function was suitable for the relationship, the R^2 of regression are 0.80 and 0.92 with a water head of 40 cm and 100 cm, and the results of statistical analysis showed that the regression is significant (p<0.05). The shape of the curve conforms to the laws of physics, that is, when the opening area is 0, the drainage flow should be 0. As the opening area increases, the growth rate of the drainage flow slows down. When the opening area is equal to the pipe wall area, the drainage flow tends to be stable. The correlation between drainage flow and opening area with a high supply water head is higher than that with a low head, indicating that the higher the supply water head is, the greater the drainage flow affected by the opening area.

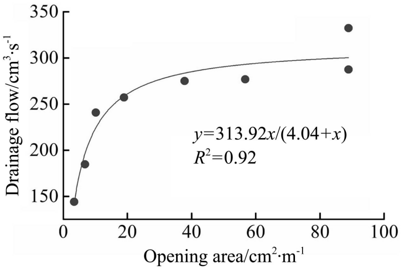
3.4.2 Effect of perforation spacing on drainage

Figure 10 shows the H-Q curves of A1 and A2, which have different perforation spacing. A1 has perforations in every valley, and A2 has perforations in every four valleys (Figure 4). To make the opening area and the number of perforations the same, A1 has two rows of perforations (two perforations in one valley), and A2 has eight rows of perforations. Under the same opening area, different perforation spacing may cause a large difference in drainage flow (Figure 10). A1 with smaller longitudinal perforation spacing has a drainage flow of approximately 15% larger than A2 with wider longitudinal perforation spacing.

Since A1 has perforations in every valley, its seepage surface area equals the area of all valleys. However, for A2, 3/4 of the valleys have no perforations, so the seepage surface area is only a quarter of A1. Therefore, the decrease in the seepage surface area resulted in a decrease in A2's drainage flow. Mohammad and Skaggs[19] also studied the effect of perforation spacing of corrugated drains, and they found that the drainage flow of drains with larger longitudinal perforation spacing was higher than that with smaller longitudinal perforation spacing. The contradictory results may be caused by the fact that he did not use envelopes, for this condition, the head loss caused by the circumferential convergence of water could be greater than that caused by the longitudinal convergence of water.



a. With a water head of 40 cm



b. With a water head of 100 cm

Figure 9 Drainage flow versus opening area of different treatments with a water head of 40 cm and 100 cm

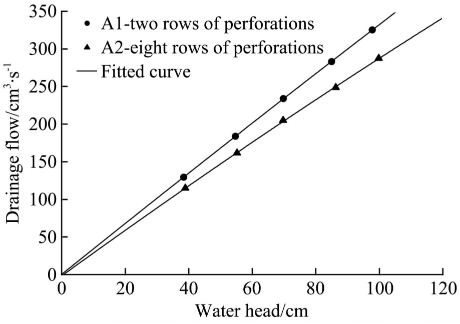
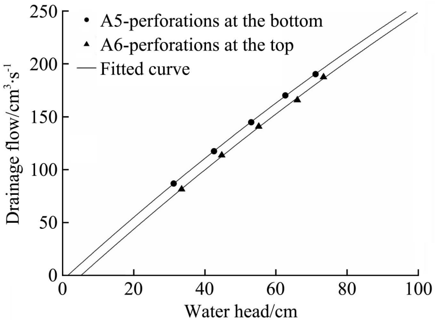


Figure 10 Drainage flow versus water head in treatments with two and eight rows of perforations

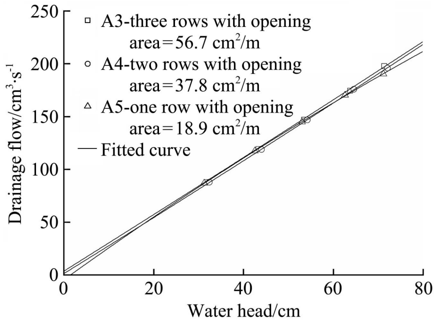
3.4.3 Effect of perforation's circumferential location on drainage

A5 and A6 used the same drain pipe that only has a row of perforations. During the experiments, the perforations of A5 were placed at the bottom of the valleys, and that of A6 was placed at the top (Figure 4). The drainage flow of A5 is 2%-11% greater than that of A6 and the lower the head is, the greater the difference will be (Figure 11a).

A3 has three rows of perforations in each valley, and its opening area is 56.7 cm^2/m, one row is at the bottom, and the two others are at the upper center position. A4 and A5 with an opening area of 37.8 cm^2/m and 18.9 cm^2/m were obtained by plugging one row and two rows at the upper part of A3 (Figure 4). Compared with A3, the drainage flow of A4 and A5, whose opening areas are 1/3 and 2/3 less than A4, was not significantly decreased (Figure 11b). Only when the head was large enough, the drainage flow of the drain with a large opening area showed a slight difference from that of the low opening area. That is, reducing the upper perforations did not reduce the drainage flow significantly, in other words, increasing the upper perforations did not significantly increase the drainage flow. This finding indicates that the water was mainly discharged from the bottom perforations, whereas the upper perforations did not drain significantly, which is consistent with the experimental phenomenon observed in Section 3.2. Not all the perforations drain, and these perforations that did not drain due to the difference of positions can be called ineffective perforations, which may become effective with the increase in drainage flow. Combined with the results of A5 and A6, the perforations at the bottom are more conducive for drainage, and if the opening area at the bottom is large enough, the upper perforations are ineffective and have no obvious promoting effect on the increase in drainage flow.



a. A5 and A6 with same opening area



b. A3, A4, and A5 with different opening area

Figure 11 Drainage flow versus water head in treatments with different perforations positions

Previous studies have different conclusions on the effect of perforation position. Schwab[31] and Mohammad and Skaggs[32] stated that perforations at the bottom were not conducive to drainage, but Luthin and Haig[13] believed that the drainage flow was greater when the perforations were at the bottom because of the increased head drop between the water table level and the entry point in the drain. Mohammad and Skaggs[19] explained the disagreement in Luthin and Haig's[13] experiments, wherein the drain did not run full so the head of the perforations of different positions varied, but in his experiments, the drain was full of water so the position of the perforations did not change the head. In the experiments of Tiligadas[29], the apparent entrance resistance of lower perforations was greater than that for the other perforations, he mentioned that this phenomenon may be attributed to the existence of a deposit of soil particles inside the drain, which caused an addition head loss for the lower perforations.

However, they all ignored the role of envelopes. Luthin and Haig[13] used envelopes in their study, and Mohammad and Skaggs'[19] experiments and Schwab's[31] theoretical analysis did not include envelopes. Whether putting perforations at the bottom is conducive to drainage depends on the hydraulic conditions around the drain pipes. When the pipes do not run full, if the permeability around the pipe wall is strong enough in which case the head loss of additional flow path is smaller than the head increased because of the change of position, the drainage flow is greater when perforations are at the bottom. If the permeability is poor, in which case the increased head cannot make up for the head loss increase, then it is better to open at the top. When the pipes are full, the inflow direction needs to be considered, that is, the closer the perforations are to the water source, the greater the drainage flow will be. In this study, the water that penetrated through the envelope will flow freely to the bottom perforations with minimal head loss because of the existence of annular space, the gravity potential was converted into pressure potential, which made it easier for water to drain from the bottom.

3.5 Characteristics of equipotential lines

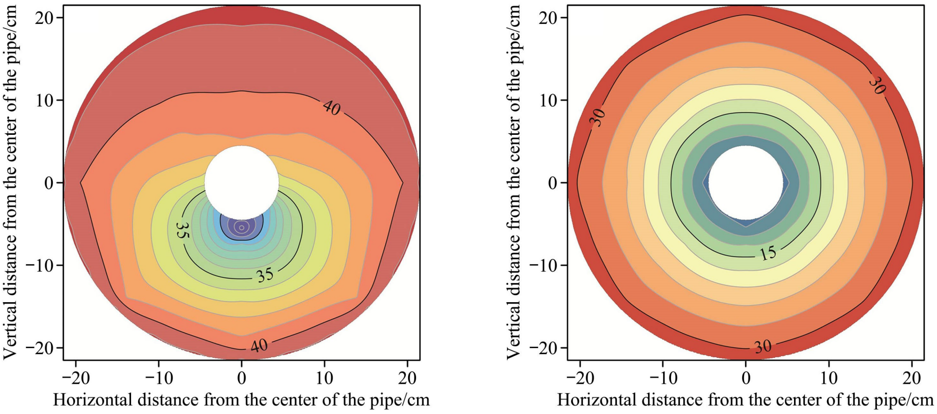
The hydraulic head distribution (equipotential lines) of different treatments and supply water heads were plotted in Figure 12. The distribution of equipotential lines has two types. One kind is of A7 or that with no envelope, and its equipotential lines protrude around the perforations, which means that the streamlines converged toward the perforations. Many studies showed that it is the convergence of streamlines that causes the additional head loss due to the limited number of perforations[9], which is reasonable for drains without envelopes. However, it is different for corrugated pipes with geotextile envelopes, as shown in Figures 12b and 12c. Although the perforation positions of A3 and A9 vary, the shapes of equipotential lines are similar to each other, and they are almost circular, which means streamlines point almost straight to the wall of the drains without converging. A9 and A7 have the same perforation positions, but the equipotential line distributions vary significantly. The reason is that the envelope made all the valleys evenly permeable, which weakened the effect of perforations on streamlines. When there was no envelope, the discontinuous perforations caused the streamlines to concentrate in the soil to several points and thus increased the head loss.

Except for the distribution of equipotential lines, we noticed a great difference in the water head at the pipe wall of different treatments. For treatments with an envelope, the water head at the pipe wall was relatively small and evenly distributed. For A7, which has no envelope, the water head at the pipe wall changed greatly, and it was low at the openings and extremely high at the impervious wall. In the case that the supply water head was 42 cm, the water head at the pipe wall of A7 reached 35 cm, so the head loss near the pipe accounted for a very high proportion.

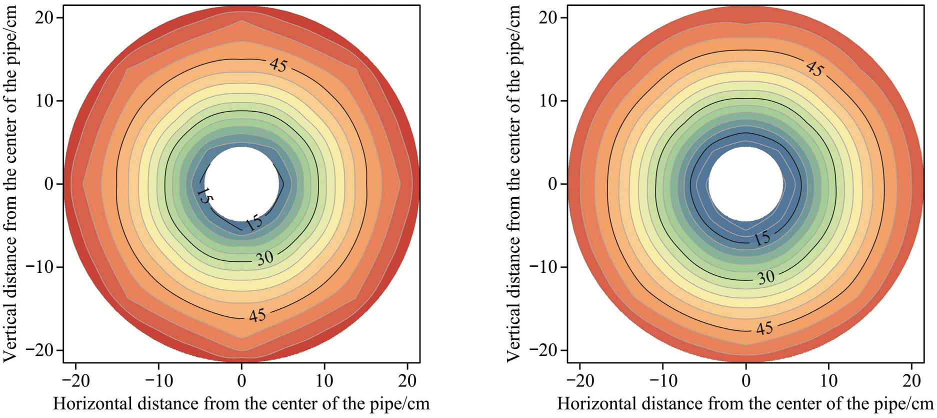
For the same treatments with different supply water heads (Figures 12b and 12c), the higher the supply water head and drainage flow were, the higher the water head at the pipe wall was. For different perforation treatments with the same supply water head (Figures 12c and 12d), the treatments which had low drainage efficiency with smaller drainage flow had higher water heads at the pipe wall. This finding suggests that low-efficiency perforations cause higher head loss at the pipe wall, which decreases the hydraulic gradient in soil.

3.6 Effective radius

It is assumed that the ideal drain is just full of water without back pressure, and the pipe perimeter is an equipotential surface, which may be taken as the arbitrary zero equipotential for convenience[10]. It is also considered that the actual equipotential lines were approximately circular. The drainage flow and water head at the edge of the sand have been measured in the experiments, so the effective radius that we called the measured effective radius can be estimated according to Equation (1). In the equation, the outer radius of sand was taken as R and the water head of the vent hole was taken as ΔH. K_S used is the measured hydraulic conductivity of sand between the second and fifth layers of piezometers of each test. Then, r, which is calculated in Equation (1), is the measured effective radius.



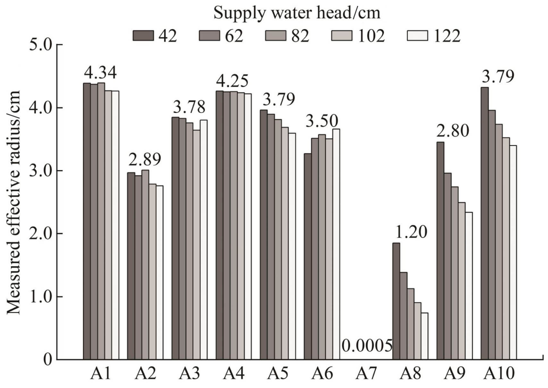
a. A7 with a supply water head of 70 cm b. A9 with a supply water head of 70 cm



c. A9 with a supply water head of 110 cm d. A3 with a supply water head of 110 cm

Figure 12 Profile equipotential lines of different treatments with water heads in different sizes

The calculated results are shown in Figure 13. Except for A6, perforations of which are at the top of the pipe, the measured effective radius of all treatments decreased with the increase of supply water head. The envelope had a great influence on the effective radius. In the study of Mohammad and Skaggs[19], effective radiuses were increased from 0.5 cm to 3.6 cm with the use of a 5 cm thick gravel envelope. In this study, the effective radius of A7 was increased from 5×10^{-4} cm to 3.79 cm by using a geotextile envelope in A5. The use of a thin and cheap geotextile envelope can increase the effective radius in the absence of a gravel envelope significantly. In the case of wrapping geotextile envelope, perforations also had a large influence on the effective radius. The effective radiuses can be less than 1 cm or close to the actual radius by taking different opening areas and perforation arrangements.



Note: The figures on the histogram are average values of effective radiuses under different water heads.

Figure 13 Effective radiuses of different treatments with different supply water heads

The theoretical effective radiuses of the corrugated drain can be calculated by Equations (3) and (7), which are shown in Figure 14. The theoretical effective radiuses are smaller than the measured values. Given that the theoretical formula was derived under the condition that the valley is filled with soil, it is more suitable for corrugated pipes without synthetic envelopes or only with granular envelopes. The use of a thin geotextile envelope increases the seepage surface area, so the theoretical formula is inapplicable in this case.

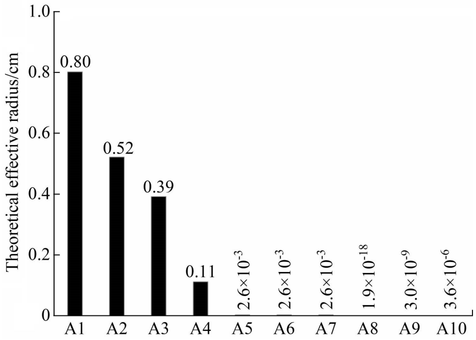


Figure 14 Theoretical effective radiuses of different treatments

The geotextile is very thin and permeable so its thickness and resistance can be ignored. If the head loss in the valley is minimal, then the drain can be generalized as a smooth pipe with annular perforations where the soil/drain interface is flat, in which case the valley with perforations can be considered an annular slit. Then, Equation (4) can be used to calculate the theoretical value of effective radiuses. For A1 and A2 with sufficiently large opening areas, the effective radiuses calculated by Equation (4), which are 4.39 cm and 2.89 cm, are close to the measured values. The measured effective radiuses are 4.39 cm and 2.97 cm under small drainage flow and 4.26 cm and 2.76 cm under large drainage flow. Considering that other treatments have perforations in each valley as A1 but a smaller opening area, the theoretical values are also 4.39 cm but higher than the measured values.

Previous studies showed that the entrance resistance depends only on the physical characteristics of the drain pipe and the envelope material[1,33]. However, some conditions that change the entrance resistance may occur in the actual tests. Lennoz-Gratin[21] and Tiligadas[29] mentioned that when the pipe is not full, the upper part of the seepage surface has surface tension, which increases entrance resistance. However, this explanation is not suitable for this study, because the effective radius did not increase with drainage flow (the larger the drainage flow, the smaller the surface area with surface tensions). Bentley and Skaggs[20] believed that the reason for the unsatisfactory results obtained by using the resistance formula of annular perforations is that the streamlines convergence caused by discontinuous perforations increased head loss. Convergence may occur in this study, but for the same perforations, the resistance also changed with opening areas and drainage flow greatly, so convergence may not be the main reason for the changes in resistance.

Hence, the explanation can be that after penetrating through the geotextile envelope, the water is further restricted by perforations where orifice entrance loss happens. Moreover, the resistance of orifice flow increases with drainage flow. To obtain an accurate effective radius, the value of drainage flow and opening area need to be considered for corrugated pipes wrapped with geotextile envelopes. The orifice entrance loss is relatively small when the drainage flow is small or the opening area is large, then the resistance formula of smooth drains with annular perforations can be used to calculate the effective radius.

4 Conclusions

To understand the effect of geotextile envelope and perforations of corrugated drains on the drainage process, a series of sand tank experiments of steady-state flow with different water heads was conducted in this study. By the combined analysis of observed experimental phenomena, H-Q curves, equipotential lines, and effective radius, the main conclusions were drawn as follows:

1) Geotextile envelope separated the valley of corrugated drains from the soil, thereby creating an annular space and increasing the seepage surface area, which changed the flow pattern around the drains and weakened the effect of perforations on streamlines. Geotextile envelope can improve the drainage capacity of corrugated drain and make the drainage flow six times that of the bare drain significantly.

2) The relationship between the drainage flow and opening areas of the geotextile-wrapped corrugated drain could be described by inverse proportional function. Meanwhile, drainage flow was affected by the perforation arrangement. Drain with small longitudinal perforation spacing had a drainage flow that was approximately 15% larger than that with larger longitudinal perforation spacing. Perforations at the bottom drained out first and were more conducive for drainage. The upper perforations are ineffective and have no obvious promoting effect on the increase in drainage flow if the bottom opening area is large enough. The drainage flow was increased by 2% to 11% when the perforations were arranged at the bottom compared with the perforations at the top.

3) The theoretical formulas of corrugated drains are suitable for drains without envelope but underestimated the effective radius of geotextile-wrapped corrugated drains. The formulas of smooth drains with annular perforations are relatively accurate when the opening area is large. The effective radius decreases with the increase in drainage flow because orifice entrance loss occurs at perforations, which causes higher water head at the pipe wall.

This study provides new insights into the effect mechanism of perforations and geotextile on flow and provides references for the values of effective radius in drainage calculation and choice of perforation pattern in pipe production for corrugated drains. For further study, behaviors of flow in valleys and the effect of different drainage materials in field drainage should be clarified and theoretical analysis of the entrance resistance is needed.

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